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**Establishment of a new lightning location system in Croatia**

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**SUMMARY**

At the end of 2008, a new lightning location system (LLS) was established as part of LINET lightning detection network, which was developed in Germany and nowadays counts over 100 sensors installed across Europe. Four sensors were installed in different parts of Croatia. Together with sensors in neighbour countries, a sensor baseline of  $\approx 250$  km has been achieved covering Croatian territory. First data analysis show satisfactory detection efficiency (DE) and location accuracy (LA) with a statistical error less than 300 m. However, conducted analyses showed that network performance improvement is possible by installing two additional sensors.

Software for real time lightning tracking with alarm function, analysis of lightning history, statistical calculations, correlation with power lines and creation of lightning density maps is being developed. Additional functionalities are in plan by connecting lightning data with SCADA, which enables a complete time and space correlation between lightning strikes and faults on transmission lines. Application of this software could provide as an effective decision making tool in control, maintenance and development of power systems. Paper shows examples of software application in power systems.

Lightning data analysis for a period of one year are conducted in order to achieve a more comprehensive statistics. Analysis will show: number and ratio of lightning detected in Croatia distributed by type and polarity in different time periods; lightning current amplitude distribution; mean and average values of current amplitude and locating error.

**KEYWORDS**

Lightning location system, LINET, GIS, spatial correlation, SCADA, relay protection, lightning data analysis

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## 1. INTRODUCTION

Tracking and surveillance of atmospheric discharges in real time and space can be an effective mean and great help in power system control. Lightning locating systems (LLS) are constantly developed and used in countries around the world for more than twenty years.

## 2. LIGHTNING LOCATING SYSTEM – LINET

European lightning locating system – LINET was developed in Germany, where 30 sensors are installed around the country. Additional 65 sensors are installed across different European countries. The established sensor network covers the most of European territory (Figure 1). In the year 2006 the LINET lightning locating system started to operate [1].

LINET uses very low and low frequency (VLF/LF) band and registers the true waveform  $B(t)$  of the magnetic flux upon an atmospheric discharge.

Main features of LINET system are:

- a) Ability to detect and locate the total atmospheric discharge with same locating error for inter-cloud (IC) and cloud-ground (CG) discharges;
- b) Great accuracy in location of both IC and CG discharges of low current amplitude;
- c) New 3D technique for a reliable discrimination of IC and CG discharges;
- d) Altitude reports for IC discharges;
- e) Locating accuracy up to 100 m.

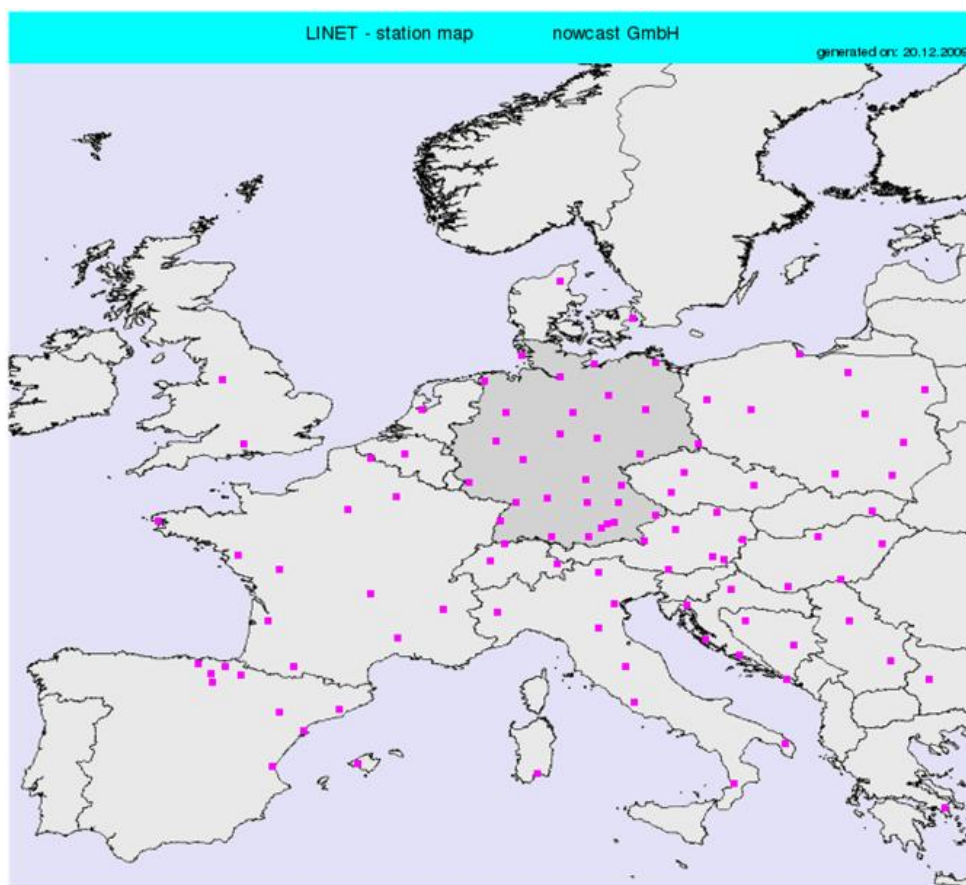


Figure 1 Location of LINET sensors in Europe [6]

## 2.1. LIGHTNING DETECTION PRINCIPLES

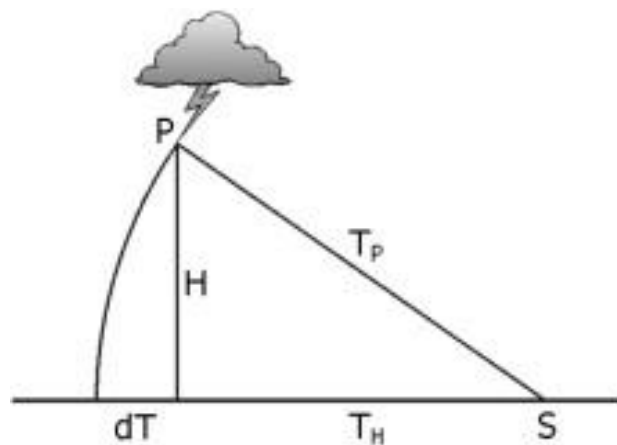
The LINET sensors measure the density of magnetic flux directly into the dependence of time. This feature is useful for the treatment of small signals. Magnetic flux component of detected signals are measured using orthogonal loop (antenna) in real time. Amplified value is induced current, not voltage, and as a result, the time dependence of the magnetic induction in the range 0.1 to 130 nT is obtained [2].

The system LINET uses TOA (Time-Of-Arrival) method for determining the location of lightning impact assisted with method for determining the direction (DF, eng. Direction Finding). Primarily TOA method is used for determining the location, where minimum four detection sensors are required. By combining TOA and DF methods the discharge can be detected by two or three sensors, but in this case, the location determine error is increased [1]. In LINET system important components are optimized to determinate all lightning discharge, including those whose amplitude is less than 5 kA, where sensors should not be too far away [3].

LINET uses the same VLF/LF method for detection of CG and IC lightning discharges [4]. Special consideration should be taken into account to distinct these two types of lightning.

For this reason, a new three-dimensional (3D) geometric algorithm for VLF / LF networks was developed [5]. The procedure relies on the well-known fact that CG strikes broadcast VLF / LF discharge dominant in ionized channel near the ground level, while IC discharge occur in the ionized channel between clouds, high above the ground. The corresponding differences in time spreading of electromagnetic waves (Figure 2) caused by high and low centers of stationary discharge were used to locate the discharge position. This method is satisfactory, as long as the distance between the lightning stroke and the nearest sensor does not exceed 100 km (corresponding to distance between sensors of 200 km), or differences in results of this method become too small to be noticeable.

All the signals are processed regardless of their waveform; this is possible because the IC-CG resolution is carried out using specially developed 3D algorithms in the central processing unit, not with measurement of waveform in sensors. This 3D technology is very reliable, especially if it is possible that the minimum distance between the sensors does not exceed 200 to 250 km.



**Figure 2 The principle of detection of IC discharge - IC and CG signals from the same 2D location come from the time difference  $dT = TP - TH$  (P = VLF emission center, S = sensor location; H = height of emission source) [1]**

Particular efforts were made to achieve high location accuracy in monitored area. Today, it is achieved that the mean location accuracy is approximately 100 m.

Output data is discharge time, location, current amplitude (including sign), the division between IC and CG discharge, discharge height for IC and 2D locating error.

LINET is capable of detecting multiple-stroke flashes where every stroke is represented by individual set of data.

A LINET sensor consist of two passive parts: the GPS antenna and the antenna for measuring magnetic flux (two orthogonal cooper rings); and one active unit – the sensor PC. Such sensor design enables the sensor to be very cost effective with a straightforward installation (Figure 3).



**Figure 3 LINET sensor antennas (orthogonal rings) and GPS antenna**

In Croatia five sensors are installed at: Dubrovnik, Split, Zadar, Rijeka and Zagreb.

### **3. SOFTWARE AND ANALYSES**

For efficient usage of data acquired by lightning locating system, adequate basic and advanced software is required. Basic software implies visualization and archiving of gathered data. With development of advanced software support, custom data analyses are available, like correlation with relay system protection and generation of lightning density maps. Software being developed is based on 3-tier architecture (Figure 4):

- a) Server-tier (database, mapping server);
- b) Web-tier (web server);
- c) Client-tier (*thin* clients – web browsers).

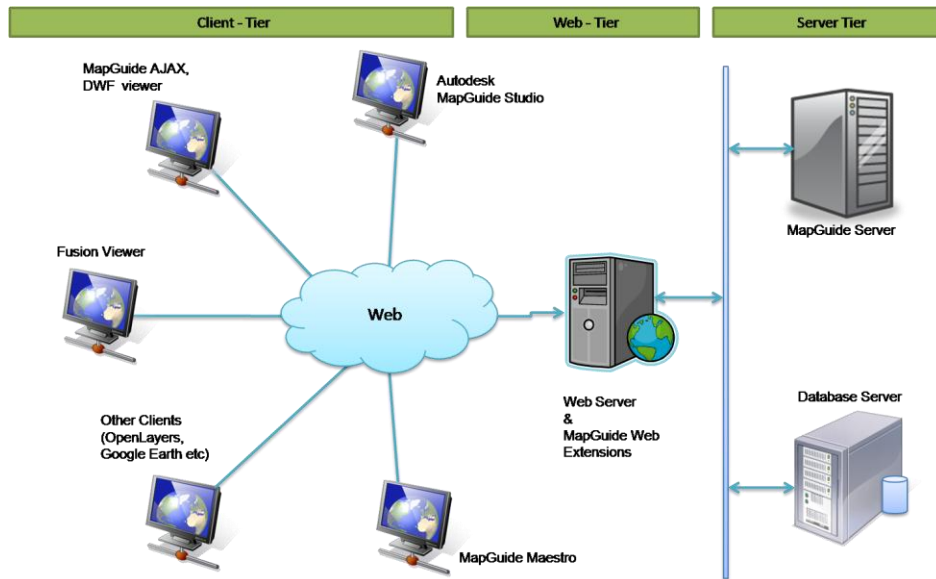


Figure 4 LLS software support – 3-tier architecture [8]

### 3.1. STORAGE OF LIGHTNING DATA

Data gathered by LINET sensors is transmitted in raw form over Internet lines to Nowcast (LINET) center where it is analysed, bind and transformed into a format ready to be transmitted to clients. Data flow is shown on Figure 5.

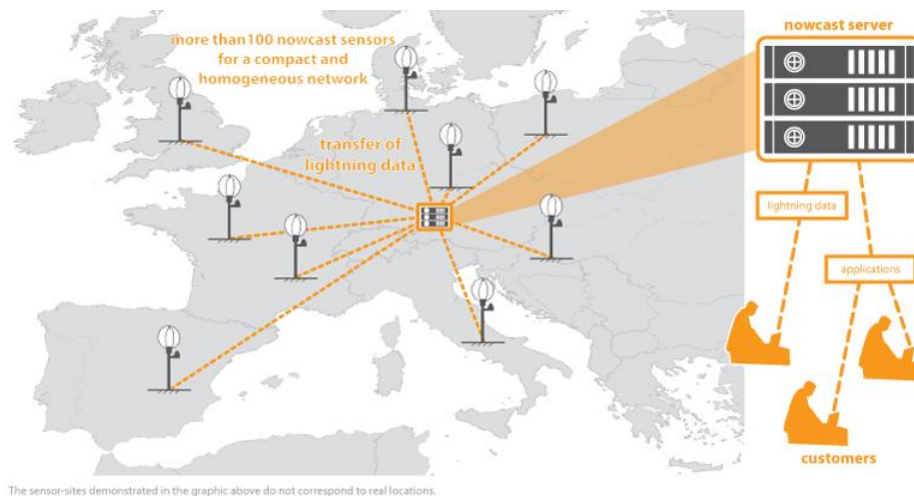


Figure 5 LINET data flow [7]

Lightning data taken from LINET sensor network is archived into a local database. Clients can access data at any time and conduct queries and analyses. Lightning data since 18<sup>th</sup> of January 2009 are available:

- Date and time (UTC, 100 ns resolution);
- GPS location – Latitude and Longitude (WGS84);
- Stroke current amplitude (0.1 kA resolution);
- Lightning discharge type (IC, CG);
- Altitude for IC discharges;
- 2D location error (meter).

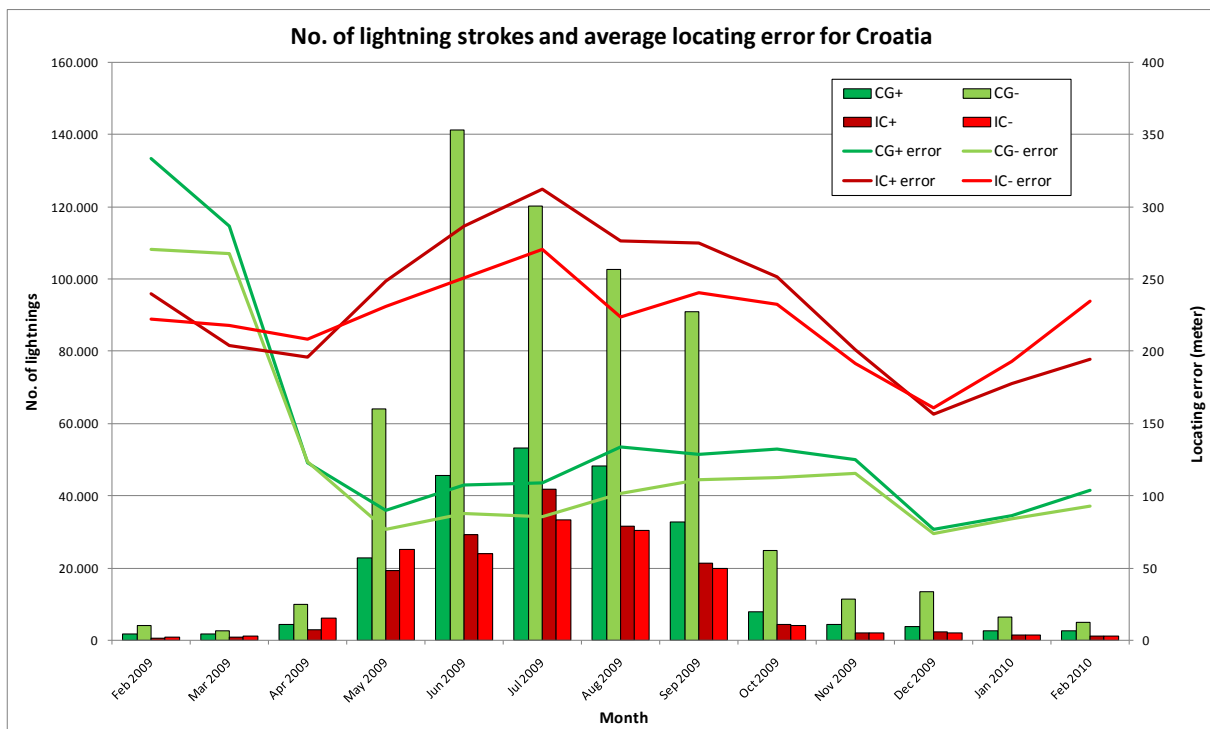
**Table 1 Lightning data:**

GPS	DATE and TIME	TYPE	ALTITUDE	CURRENT	ERROR
15.8932 45.7170	29.4.2009 18:57:05.5952183	CG	-	-15 kA	42 m
15.8920 45.7036	29.4.2009 19:07:32.7712689	CG	-	-5.2 kA	57 m
15.8508 45.7407	29.4.2009 18:50:47.1437623	CG	-	72.2 kA	54 m
15.8502 45.7388	29.4.2009 19:00:03.8719696	CG	-	8.1 kA	67 m
15.8914 45.7283	29.4.2009 19:00:03.9402258	CG	-	-2.9 kA	81 m
15.8214 45.7566	29.4.2009 18:50:47.1127271	IC	3600 (m)	-5.5 kA	58 m
15.8963 45.7263	29.4.2009 19:09:53.8456357	IC	4800 (m)	7.4 kA	63 m
15.8647 45.7595	29.4.2009 19:07:01.6730042	IC	4100 (m)	4.7 kA	60 m
15.8117 45.7558	29.4.2009 18:49:09.4577769	IC	5900 (m)	-10.7 kA	89 m

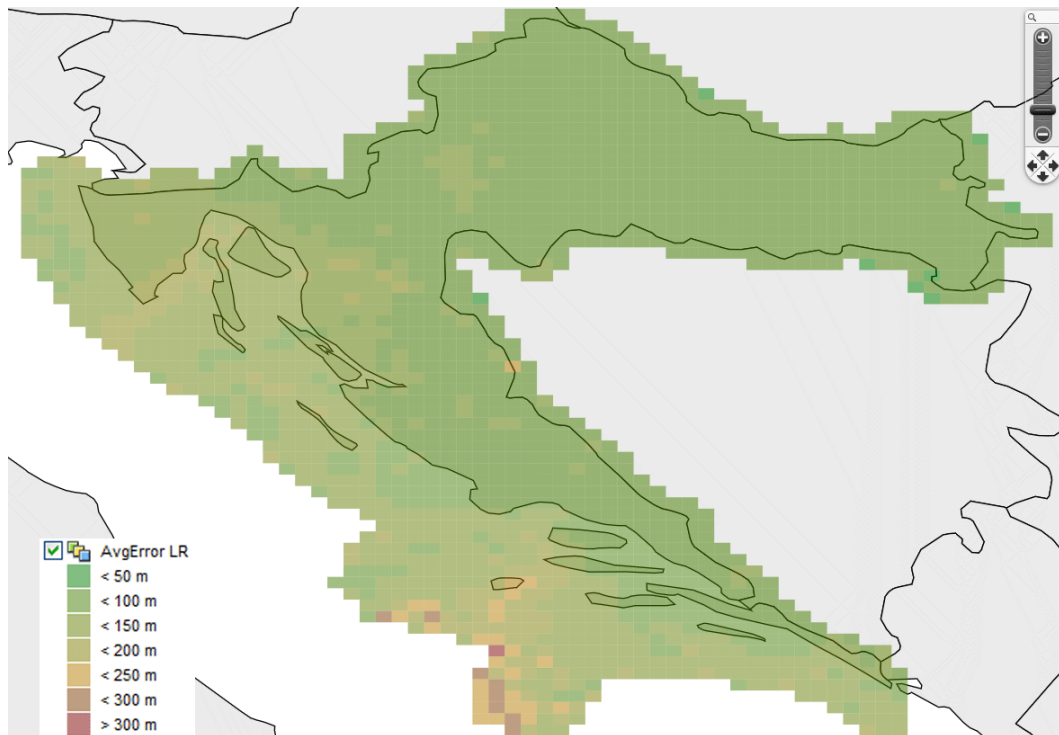
Figure 6 shows number of lightnings detected in Croatia and the average locating (statistical) error, distributed by month. Territory of Croatia with a 3 km buffer (100 348 km<sup>2</sup>) is taken while performing spatial analyses.

**Table 2 No. of lightning strokes in Croatia in 1 year period**

CG+	CG-	IC+	IC-
230 000	592 741	158 205	150 568

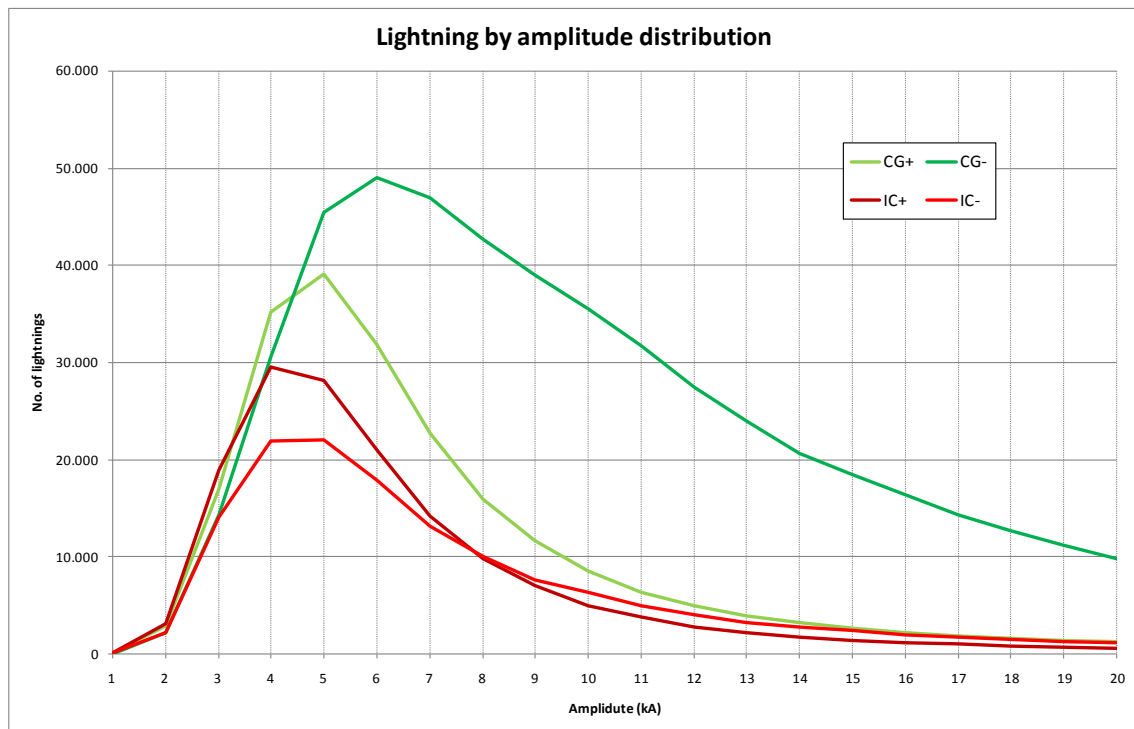
**Figure 6 Number of lightning and average locating error in Croatia**

After one year of gathering data, an error map has been formed showing the statistical error of lightning data. With 5 sensors inside Croatia and additional 20 sensors in neighbour countries, average locating error across Croatia varies from 50 to 150 m (Figure 7).



**Figure 7 LLS Average locating error map (0.05° grid)**

Lightning amplitude distribution graph (Figure 8) shows a good detection of strokes including small amplitude lightning.



**Figure 8 Amplitude distribution of lightning in Croatia in 1 year period**



### 3.2. LIGHTNING DATA VISUALIZATION

An effective lightning locating system should cover a wider geographic area, like the south-east of Europe where Croatia is located. Lightning visualization (Figure 9 and Figure 10) enables immediate sensing of lightning storm encounter, which helps in power system management assuring the time needed for implementing appropriate security measures. Storm evolvment and CG – IC ratio for the monitored storm is depicted in Figure 11.

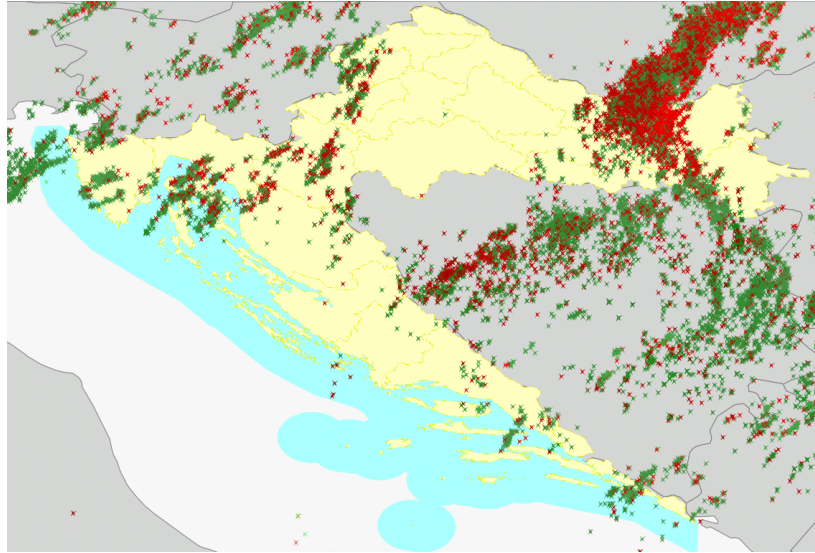


Figure 9 Lightning activity over Croatia on 1st of May 2009 (green – CG, red – IC)

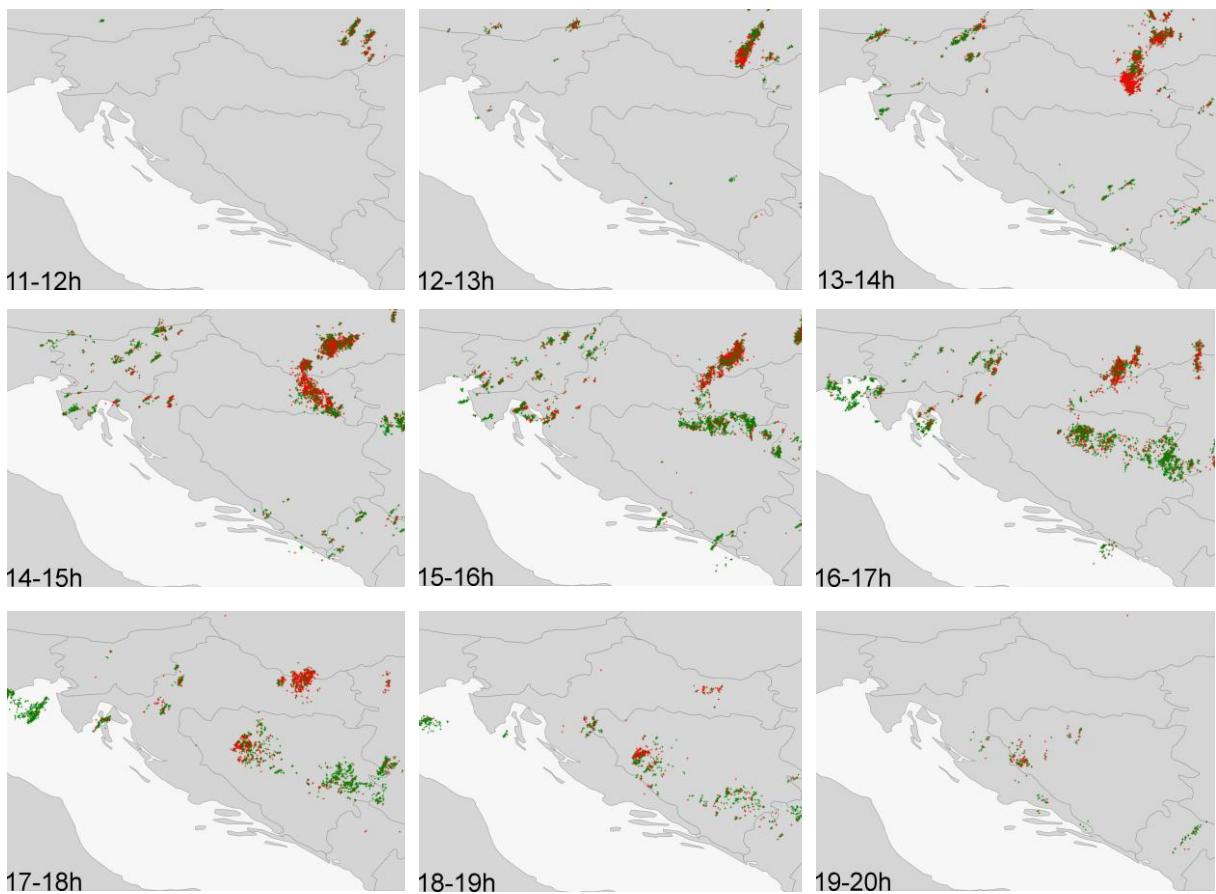
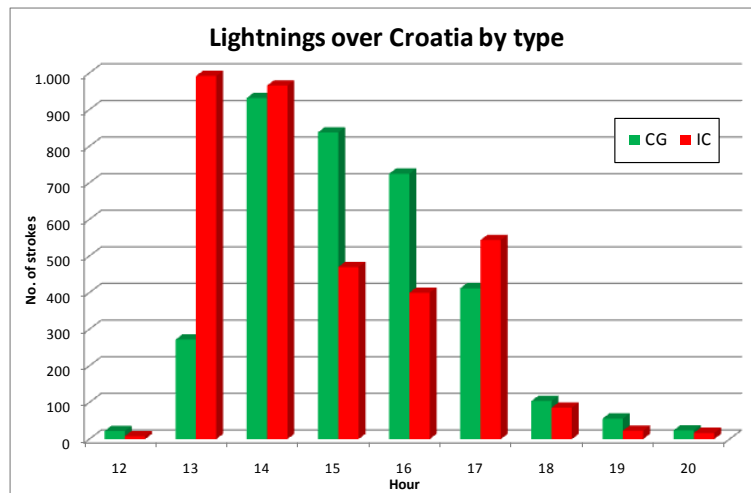


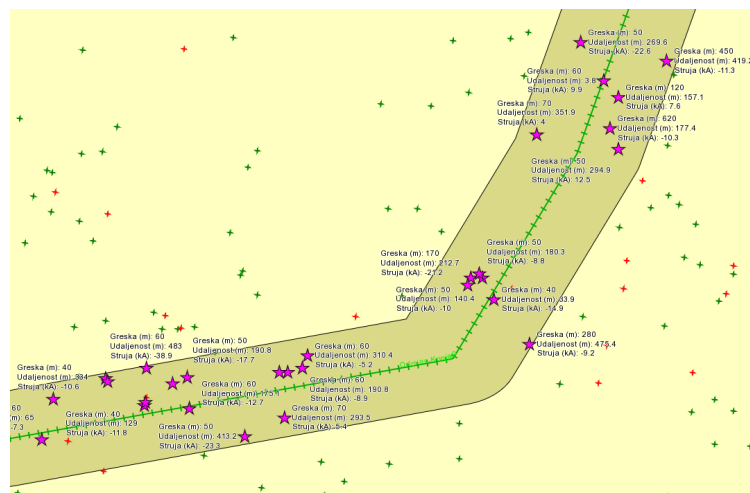
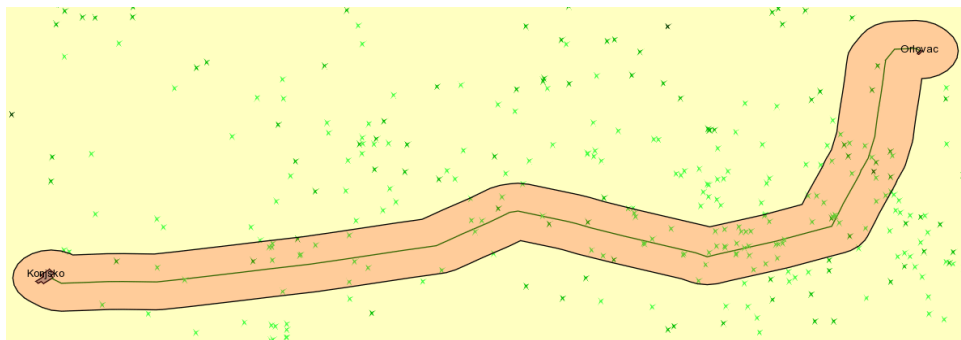
Figure 10 Monitoring of lightning storm over Croatia on 1st of May 2009 (green – CG, red – IC)





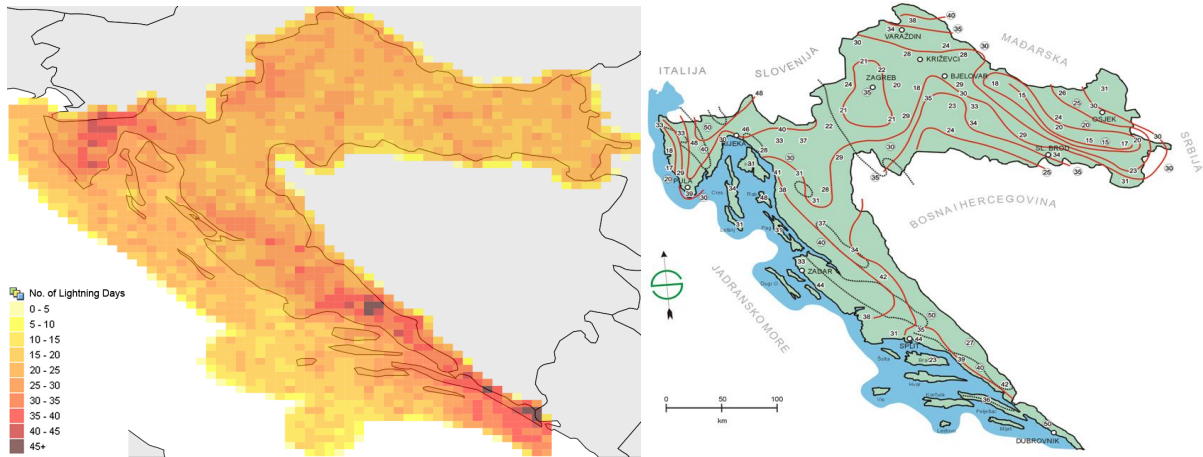
### 3.3. SPATIAL CORRELATION WITH GIS DATA

GIS (Geographic Information System) data of transmission lines and substations are linked with LLS data, i.e. precise location and time of atmospheric discharge. GIS is a software decision making tool for gathering, storage, querying, analysing and viewing of spatial data. Using GIS software it is easier to locate faults on transmission lines caused by lightning strikes, so service teams can be rapidly and precisely deployed. Figure 12 and Figure 13 show an example of lightning detection inside a 500 m radius buffer of a double-circuit 220 kV line during a storm in Croatia.



### 3.4. CREATION OF ISOKERAUNIC AND DENSITY MAPS

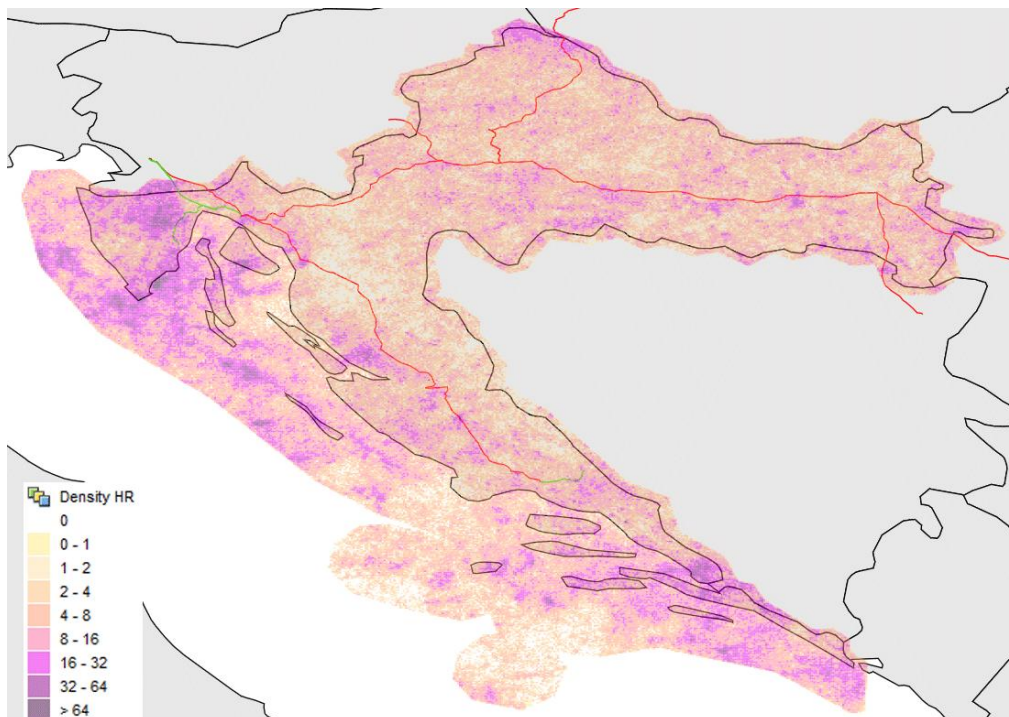
Isokeraunic maps display number of lightning days per year for a specified territory. Lightning data has been used to create a isokeraunic map of Croatia. Results have been compared with existing isokeraunic map (Figure 14) [9] showing good overlap.



**Figure 14 LLS created isokeraunic map compared to previously created party map**

An important function of lightning locating system is generation of lightning density maps (Figure 15), especially around transmission lines and substations. This data is a great decision making help to engineers while choosing adequate protection (e.g. surge arresters) and finding the optimal location for protection installation.

For better understanding of density maps displayed in this paper, an explanation will be given. As lightning data obtained from LINET records each stroke as an individual set of data, and stroke multiplicity is a well known fact [10] (especially for negative CG flashes), density maps will display noticeable higher values. Additionally, time period of one year may be too short to represent a detailed distribution.



**Figure 15 Density map for Croatia (1 year period, 1km grid, individual strokes)**

For each transmission line high-resolution density map (Figure 16) can be made and the most exposed sections can be located. With analyse of lightning currents and polarities, optimal protection can be chosen. Lightning density maps can be used for determination of optimal routes for building new transmission lines, avoiding exposed areas, thus minimising the risks of failure. Lightning density is calculated by formula (1):

$$N_g = \frac{n}{A \cdot t} \left[ \text{strokes} / \text{km}^2 / \text{year} \right] \quad (1)$$

$n$  – no. of strokes;  $A$  – area ( $\text{km}^2$ );  $t$  – time period (years)

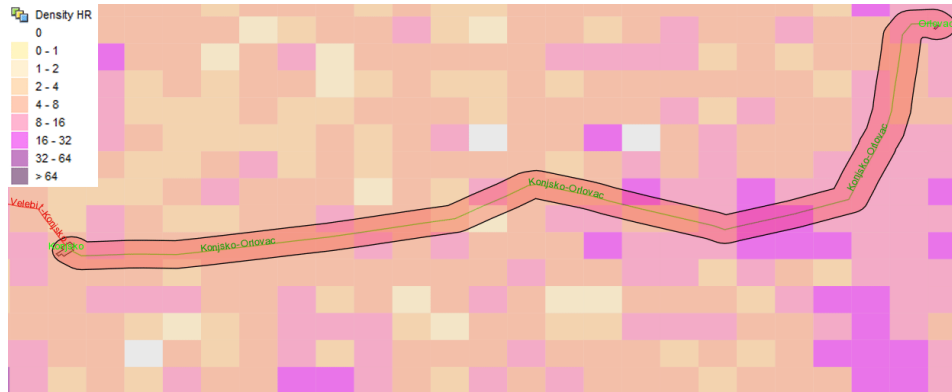


Figure 16 Density map (1 year period, 1km grid, individual strokes)

### 3.5. CORRELATION WITH SCADA

Lightning locating system can be linked to SCADA, correlating in real-time events registered in the power system (faults, automatic reclosures, etc.) with lightning data. If correlated with GIS data of transmission lines and substations, very accurate time and space correlations are possible. Correlations can be displayed on map in near real-time.

Figure 17 shows a simplified correlation schema.

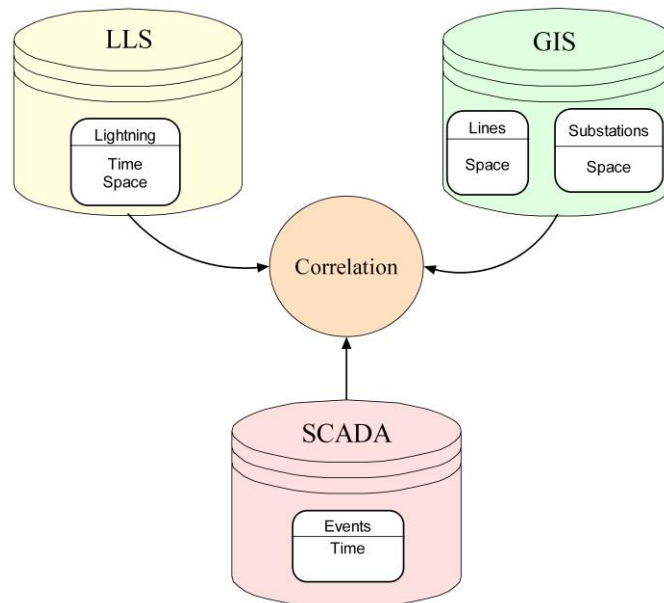


Figure 17 Correlation schema LLS - GIS – SCADA

A short example of correlation is given to demonstrate the time-space correlation of LLS, GIS and SCADA.

Lightning data has been correlated with SCADA events and proximate (500 m error) GIS data of a double-circuit 220 kV line connecting hydropower plant (HPP) and a substation. HPP registered failures on both circuits at 16:27 local time (more precise time information is not available). LLS registered 3 strikes (2 of them are multiple) as candidates causing the failures (Table 3). For more precise discrimination, GPS synchronization of SCADA is needed.

**Table 3 Lightning candidates causing failures on the double-circuit 220 kV line**

GPS location	Date and time	Amplitude	Location error
16.7177 43.6103	4.5.2009 16:26:12.8821294	-25 (kA)	40 m
16.6969 43.6126	4.5.2009 16:26:12.9216174	-14.7 (kA)	40 m
16.7242 43.6112	4.5.2009 16:26:56.8094749	-38.9 (kA)	60 m
16.7205 43.6099	4.5.2009 16:26:56.8322992	-25.5 (kA)	40 m
16.7203 43.6102	4.5.2009 16:26:57.1222884	-9.8 (kA)	60 m

#### 4. CONCLUSION

Lightning locating systems continuously improve and evolve, and nowadays are a powerful tool in planning, protection and management of power systems. LLS are also used in other technological systems and networks, e.g. telecommunication, transmitter and repeater stations, oil and gas pipelines, insurance companies, military, meteorology, air travel, fire department, etc. This paper demonstrates a lightning locating system applied in power systems. First lightning data has been archived and analysed. Archived data shows good detection efficiency and locating accuracy. Lightning data has been correlated with GIS data of transmission lines and events in power system gathered from SCADA. Analyses demonstrated positive impacts of LLS in management of power system. Correlated data can improve response time for repairs and minimize faults caused by lightning strikes.

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